Determination of root-zone water storage in a desert woodland using a two-layer moisture balance model

YONGHUA ZHU[1], LILIANG REN[1], HAISHEN LÜ[1] & T. H. SKAGGS[2]

1 *State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China*
yonghua321@yahoo.com.cn
2 *US Salinity Laboratory, 450 W. Big Springs Rd., Riverside, California 92507, USA*

Abstract Root-zone water storage (RWS) is a fundamental component of the soil–plant–atmosphere continuum. In the lower reaches of arid river basins in inland China, low water recharge and hence low RWS have been associated with a series of ecological and environmental problems. Developing an improved understanding of RWS, as well as methods for estimating RWS, will permit improved water management and help achieve sustainable development in these arid basins. In this study, the temporal variation of RWS under the natural undershrub *Sophora alopecuroides* was examined at an experimental site located in the Ejina basin of northwest China. RWS was modelled using a two-layer soil moisture balance model comprising a shallow surface layer (0–10 cm) and a root-zone layer. Model simulations were found to be in very good agreement with experimental data. Possible future applications include regional RWS assessments in northwestern China in which the model surface layer is correlated with remote-sensing measurements of surface moisture content.

Key words root-zone water storage; two-layer soil moisture balance model

INTRODUCTION

In many agricultural and hydrological applications, RWS is an important variable because of its impact on plant growth and on the water balance at the land surface. Defined as the amount of water per unit area in the root-zone, RWS is commonly determined based on field measurements of soil water content. However, such field measurements can be time consuming and expensive to obtain. Furthermore, when considering regional scale RWS, these data are point measurements that are difficult to interpolate or extrapolate to the larger scale because of the spatial variability of soil properties and the scarcity of data in time and space.

Microwave remote sensing of soil moisture over large areas is a possible alternative to field measurements. However, microwave remote sensing usually only provides data for surface soil layers (0–10 cm). A method for estimating RWS based on remotely-sensed measurements of the surface soil moisture content would be extremely useful for the study of regional scale soil moisture. A number of authors previously investigated this estimation problem using a two-layer model, where the first layer is a shallow surface layer and the second is the root zone (e.g. Deardorff, 1977; Wigneron *et al.*, 1999; Montaldo & Albertson, 2003). For the most part, these studies have considered only grasslands (Montaldo & Albertson, 2003) or cropped areas (Ragab, 1995; Wigneron *et al.*, 1999) where moisture enters the soil predominately from the surface (due to precipitation or irrigation) and where root zones are shallow (~50 cm).

In extremely arid regions of China where precipitation is very low, plant growth is correspondingly small and is dependent on phreatic evaporation, which transfers water from shallow water tables up to the root zone. The two-layer moisture models noted previously did not consider phreatic evaporation, nor were they tested for conditions of deep-rooted plants. The objective of this paper is to test a two-layer model for conditions of phreatic evaporation and deep plant rooting. We estimate the temporal evolution of RWS under a perennial riverside undershrub *Sophora alopecuroides* (*S. alopecuroides*) in the Ejina basin of northwest China. The model is found to be in good agreement with experimental data. The success of the two-layer model under these conditions suggests the model may be useful in future applications involving remote-sensed soil moisture data in western China and elsewhere.

EXPERIMENTAL LOCATION AND METHODS

An investigation of the temporal variability of soil moisture was conducted at a Chinese Academy of Sciences eco-hydrological research site in the extremely arid woodlands (40°10′–42°30′N, 99°25′–102°00′E, 940.5 m above sea level). The Ejina basin is near the northeastern edge of the Badanjilin desert and in the lower reaches of the Heihe River basin, the second largest inland river basin in arid northwest China (Fig.1). The experimental site is 4 km southwest of Ejina City. Mean annual precipitation is 38.24 mm, mean annual free water surface evaporation is 3631.9 mm, and average temperature is 8°C. The undershrub *S. alopecuroides* in the experimental woodland has not been significantly affected by human activities. The experimental site is 10 000 m^2 and is 200 m from the river. The groundwater depth ranges from 1.5 to 3 m.
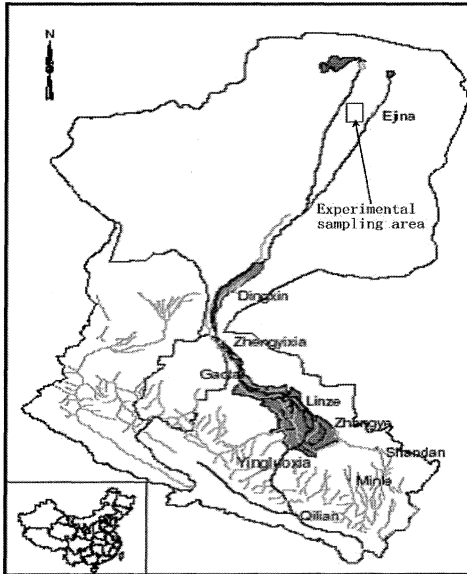

Fig. 1 The scheme of the study region.

The experimental area was divided into 10 sections. Within each section, a site with soil representative of the whole section was chosen for measuring soil moisture. Soil moisture measurements continued for three years (2003–2005), beginning each year on 1 May and ending on 31 October. Soil cores to a depth of 140 cm were obtained with an augur every 5 days. The cores were sectioned into eight layers: 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, 100–120 cm, and 120–140 cm. From within each layer, three replicate subsamples were taken near the midpoint of each layer. The subsamples were weighed, dried at 105°C, and re-weighed to determine soil moisture.

Starting on 23 September 2004 and ending 31 September 2004, measurements were made of effective root length. One shrub was selected from each of the 10 experimental sections. A soil column centred beneath the shrub and measuring 60 cm in diameter and 140 cm deep was excavated and sectioned into eight layers: 0.0–10.0 cm, 10.0–20.0 cm, 20.0–31.5 cm, 31.5–61.5 cm, 61.5–94.5 cm, 94.5–127.5 cm, 127.5–135.0 cm, and 135.0–140.0 cm. The soil layers were sieved and root diameters and lengths were measured. All roots with diameter less than 0.4 cm were classified as effective roots, presumed active in absorbing moisture from the soil (Zhu, 2002).

The soil at the experimental site is mainly fine sand, so the soil was treated as a homogeneous fine sand with a field capacity soil moisture content of 31.7% and a wilting point water capacity of

0.73% (Feng & Chen, 1999). Daily weather data were obtained from the Ejina County Weather Station.

SIMULATION METHOD

Two-layer soil moisture balance model

The two-layer soil moisture balance model is given by:

$$\frac{\partial \theta_s}{\partial t} = \frac{P + E_{g_s} - E_s}{d_s} - C(\theta_s - \theta_{rz})$$

$$\frac{\partial \theta_{rz}}{\partial t} = \frac{P + E_{g_{rz}} - R - E_{rz}}{d_{rz}}$$

(1)

where θ_s is the volumetric water content of the surface layer (0–10 cm) (cm^3 cm^{-3}), θ_{rz} is the volumetric water content in root-zone (cm^3 cm^{-3}), P is the precipitation rate (mm day^{-1}), E_g is the rate of phreatic evaporation reaching to the surface layer (mm day^{-1}), E_s is the surface evaporation (mm day^{-1}), d_s is the depth of the surface layer (mm), C is the pseudo-diffusivity coefficient (day^{-1}) that is a function of the surface and root-zone soil moisture content and the thickness of the two layers, $E_{g_{rz}}$ is the phreatic evaporation reaching to root-zone (mm day^{-1}), E_{rz} is the root-zone evaporation (mm day^{-1}), R is deep drainage (mm day^{-1}), and d_{rz} is the root-zone depth (mm).

Determination of input parameters

Phreatic evaporation The phreatic evaporation rate was determined using the following formulas (Mao *et al.*, 1999):

$$E_{g_{rz}} = E_0 \left[1 - \frac{h - d_r}{h_0} \right]^m$$

(2)

$$E_{g_s} = E_0 \left[1 - \frac{h - 0.01}{h_0} \right]^m$$

(3)

where d_r is the depth of the effective root-zone (m), E_0 is the daily average potential evaporation during the period Δt (mm day^{-1}), h is the average depth of the water table during Δt (m), h_0 is the water table depth below which phreatic evaporation ceases (m), and m is an empirical parameter that is a function of soil characteristics, climate, etc. and which takes on different values during the growth periods of *S. alopecuroides*. In this paper, m was determined for each month of its growth period by fitting equations (2) and (3) to data measured by Liu *et al.* (2005). The fitted parameter values are given in Table 1.

Table 1 Index *m* for different months during the growth period of *S. alopecuroides*.

Month	May	June	Jul.	Aug.	Sep.	Oct.
m	6.86	5.85	4.30	6.30	6.52	9.00

For the *S. alopecuroides* woodland we studied, d_r was 1.4 m and h_0 was 4.72 m, the latter estimate being based on the work of Feng (1998).

Actual evapotranspiration Actual evapotranspiration (*ET*) was calculated by multiplying potential evapotranspiration (*PET*) by a reduction factor that depends on the moisture content of the soil. For these purposes, the soil profile was divided into the same 8 layers indicated above for the soil moisture measurements. Transpiration and uptake were assumed to be at potential levels

when the soil was at field capacity, and decline linearly with decreasing available. Letting i index the day of measurement (from 1 May to 31 October) and j the soil layer ($1 \leq j \leq 11$), available water was calculated as (Ragab, 1995):

$$SI(i,j) = \frac{\theta(i,j) - \theta_{\text{wilting point}}}{\theta_{\text{field capacity}} - \theta_{\text{wilting point}}} \tag{4}$$

The actual evapotranspiration, *ET*, was then calculated as:

$$ET(i,j) = SI(i,j)PET(i) \tag{5}$$

Potential evapotranspiration, *PET*, was calculated from weather data using the method of Stockle *et al.* (1992).

Initial values of moisture content According to Camillo & Schmugge (1983) and Ragab (1995), under conditions of a fully grown root system and sufficiently dry soil, root-zone soil moisture storage W_{rz} (cm) can be obtained by multiplying the volumetric moisture content of the surface layer θ_s by a constant of proportionality $I(z_s)$. As shown in equation (6), the constant of proportionality is calculated from the root density distribution:

$$W_{rz} = \theta_s I(z_s)$$
$$I(z_s) = \int_{\substack{\text{root} \\ \text{zone}}} \left[\frac{R(z_s)}{R(z)} \right]^{\frac{1}{bn}} dz \tag{6}$$

Here, $R(z_s)$ is the relative root density (m^{-2}) in the surface layer, $R(z)$ is the relative root density (m^{-2}) in the root-zone, b is a soil texture parameter, and n is a parameter that depends on the functional form of $R(z)$.

The growth period of *S. alopecuroides* in the Ejina basin is from May to October, with the dry period beginning in September. Thus from September to October, the soil moisture distribution is controlled mainly by phreatic evaporation and the sorption of moisture by roots, and equation (6) can be used to estimate the profile moisture content from measurements of the surface layer if $I(z_s)$ can be determined. Following Camillo & Schmugge (1983), the soil texture parameter b at the experimental site is given as 4.05 and, we calculated $n = 2 + \frac{2}{b} = 2.49$. The root measurement data (length of root per volume of soil) resulted in the following root distribution density function (cm^{-2}) for *S. alopecuroides* (average distribution for the 10 sections):

$$R(z) = \begin{cases} 0.0157 & 0.0 \leq z \leq 10.0 \text{ cm} \\ 0.0101 & 10.0 < z \leq 20.0 \text{ cm} \\ 0.0398 & 20.0 < z \leq 31.5 \text{ cm} \\ 0.0898 & 31.5 < z \leq 61.5 \text{ cm} \\ 0.1630 & 61.5 < z \leq 94.5 \text{ cm} \\ 0.0393 & 94.5 < z \leq 127.5 \text{ cm} \\ 0.4561 & 127.5 < z \leq 135.0 \text{ cm} \\ 0.9279 & 135.0 < z \leq 140.0 \text{ cm} \\ 0.0000 & z > 140.0 \text{ cm} \end{cases}$$

With this root distribution, the proportionality coefficient in equation (6) for the 0–10 cm surface layer $I(z_s)$ was:

$$I(z_s) = 1211.91 \tag{7}$$

Pseudo-diffusivity coefficient C Ragab (1995) discussed several possible values for the pseudo-diffusivity coefficient C. We took C to be equal to 0.0492, a value roughly in the middle of those discussed by Ragab (1995).

Simulation procedures

The initial day of the simulation was 1 September 2005. Although the initial value of the surface layer moisture content could in principle be obtained by remote sensing, our object was to first verify that the two-layer model was appropriate for situations with phreatic evaporation, and we initialized the surface layer with the measured gravimetric water content. The initial value of the root-zone moisture content was then determined by equations (6) and (7). Finally, equation (1) was solved using divided differences and a daily time step to compute the time variation of root-zone soil moisture. Because 1 September is in the middle of the growth period of *S. alopecuroides*, the simulation was done both forward and backward from this date so that RWS would be computed for the entire growth period.

RESULTS AND DISCUSSION

A comparison of simulated $W_{rz_{simulated}}$ and observed $W_{rz_{iobserved}}$ RWS is shown in Fig. 2. The data are the averaged values from the 10 experimental sites. The root-mean-square error (r.m.s.) and the relative mean error (r.m.e.) are calculated by the following formulas, respectively:

$$r.m.s. = \left\{ \frac{1}{N} \sum_{i=1}^{N} \left[W_{rz_{i\,observed}} - W_{rz_{i\,simulated}} \right]^2 \right\}^{\frac{1}{2}} \quad r.m.e. = \frac{1}{N} \sum_{i=1}^{N} \left[\frac{W_{rz_{i\,observed}} - W_{rz_{i\,simulated}}}{W_{rz_{i\,observed}}} \right]$$

The calculated r.m.s. and r.m.e. for the root-zone were 1.15 cm and 1.25%, respectively. These goodness-of-fit values, as well as visual inspection of Fig. 2, indicate that prediction errors are low and that the simulated values agree very well with the data. Figure 2 also shows that the simulated RWS has larger fluctuations in the early part of the growing season than in the later. The reason is that it in the early part of the growing season, *S. alopecuroides* grows fast and, with a daily time step, phreatic evaporation may lag behind evapotranspiration, leading to oscillatory behaviour. Later in the season, the plant grows more slowly and the system is less dynamic and closer to an equilibrium condition.
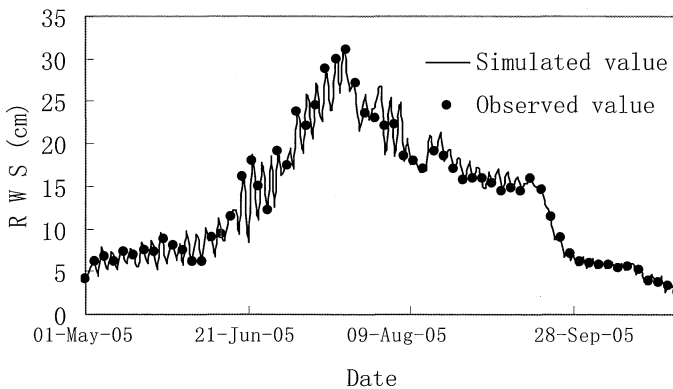

Fig. 2 The comparison of simulated and observed RWS for *S. alopecuroides*.

CONCLUSIONS

This study investigated temporal changes in RWS in a natural desert woodland with undershrub *S. alopecuroides*. Located in Ejina Basin, China, the experimental woodland is extremely arid and

plants rely on phreatic evaporation as a primary water source. A two-layer model of RWS was developed and tested using surface soil moisture measurements to initialize the simulated root zone storage. The simulated RWS was in good agreement with experimental data. The observation errors were low (the r.m.s and r.m.e were 1.15 cm and 1.25%, respectively), indicating that the two-layer model is reliable for landscapes in which phreatic evaporation is a significant component of the water balance. Because the two-layer model can be initialized with measurements of surface soil moisture, the model may be used in conjunction with remotely-sensed soil moisture data.

This study considered only temporal changes in RWS at a single (averaged) location during the growth period. Future studies should focus on the spatial component of RWS and the incorporation of the two-layer model into a distributed hydrological model. Additionally, this study considered only the undershrub *S. alopecuroides* growing in an arid desert region. Future studies should focus on additional plants and climates.

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